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Driving pattern analysis of Nordic region based on National Travel Surveys for electric vehicle integration

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Abstract Electic vehicles (EVs) show great potential to cope with the intermittency of renewable energy sources (RES) and provide demand side flexibility required by the smart grid. Furthermore, EVs will increase the electricity consumption. Large scale integration of EVs will probably have substantial impacts on power systems. This paper presents a methodology to transform driving behavior of person into one of the cars in order to analyze the driving pattern of EVs based on the National Travel Surveys. In the proposed methodology, a statistical process is used to obtain the driving behavior of cars by grouping the survey respondents according to the driving license number and car number, and mapping the households with similar characteristics. The proposed methodology was used to carry out the driving pattern analysis in the Nordic region. The detailed driving requirements and charging/discharging availability of vehicles along the day were obtained. Two types of EV availabilities were studied in this paper considering different charging/discharging conditions of EVs for the power system integration, i.e. EV availability all day and EV availability at home. The results show that the daily driving requirements of the Nordic region are not very intensive. The driving patterns of vehicles in the Nordic region vary on weekdays and weekends. The two types of EV availabilities are quite different from each other.

Keywords Driving pattern, Electric vehicles (EVs), EV availability, Nordic, Power system integration

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1 Introduction

Driven by growing concerns on greenhouse gas (GHG) emission and energy independence from fossil fuels, electric vehicles (EVs) have been promoted around the world for the past few decades. Being considered as a type of distributed energy resource (DER), EVs show great potential to handle the fluctuation due to further utilization of renewable energy sources (RES) in future power systems and provide demand side flexibility required by smart grid. Such motivations are aligned with the Nordic power system development. The Nordic region including Denmark (DK), Finland (FI), Norway (NO) and Sweden (SE) is aiming at achieving a sustainable energy system by 2050 in [1–6]. EV is an important part of the plans for the ambitious goal. In this context, the integration study of EVs is of great importance and has strong necessities in the four mentioned Nordic countries.

The study of the impact on EV charging for the grid started in the 1970s in [7]. A number of studies on this topic have been carried out ever since in [8–14]. In recent years, the EV integration and vehicle-to-grid (V2G) technologies have been researched with the assumption of large scale deployment of EVs in [10, 14–21]. Regarding the Nordic area, integration studies of EVs were carried out in different countries. The research in [22, 23] studied the charging demand based on the case of Danish island of Bornholm. Reference [24] introduced the EV fleet integration on Bornholm with virtual power plant (VPP) concept. An optimal charging model was built according to the survey data of Western Denmark in [25]. The integration of a V2G system was analyzed in the Western Danish power grid in [26]. Reference [27] estimated the charging cost of EVs in the Finnish context. The Finnish national travel survey based load models were used to calculate the impacts of EVs to the distribution networks in [28]. Reference [29] studied and built detailed models of the stochastic charging load of the plug-in hybrid electric vehicles (PHEVs) in Finland. However, in most of EV integration studies, the detailed driving patterns of EVs are not considered. The simplification of driving pattern might lead to inaccurate results in EV integration studies.

Driven by different motivations, many studies focusing on different aspects of vehicle driving patterns have been carried out. For example, the speed and acceleration profiles were studied to estimate the emission and fuel use of vehicles in [30–32]. The driving pattern prediction on a specific driving course for the energy management of vehicles was carried out in [33]. The driving data in China to develop the driving cycle for the purpose of vehicle emissions and energy consumption estimation and traffic impact assessment was studied in [34]. The GPS based data was used to develop a duty cycle for the plug-in vehicles in the North American urban setting in [35]. GPS based information collected over one month from 360 vehicles to assess the feasibility of EVs in Copenhagen in [36]. The daily driving requirements of vehicle drivers were analyzed with GPS-based driving information collected from 484 vehicles for in Atlanta of the United States in [37]. Reference [38] used the real-world driving data that comprise 4409 trips in Southeast Michigan of the United States to build a model of the daily driving mission for studies of real-world PHEV usage. It is developed a driving pattern recognition method for EV range estimation in [39]. The travel data from the Transportation Tomorrow Survey in Toronto was used to study the impacts of driving patterns on tank-to-wheel energy use of PHEVs in [40]. The driving data was studied in Australia from GPS devices to access the feasibility of battery electric vehicles (BEV) in [41]. The data of 11 EVs and 23 charging stations from the Western Australia Electric Vehicle Trial was analyzed in order to obtain the features of the EV charging events in [42]. The daily and yearly driving pattern in France were analyzed to compare the competitiveness of electric driving with different power train technologies [43].

Most of the driving pattern studies at present serve the purposes of emission and energy consumption assessment of conventional vehicles, driving energy management, feasibility evaluation and driving range estimation of EVs. Generally, they focus on single driving cycle analysis, driving status recognition or daily driving distance range quantification. However, the EV integration study on the power system has its own concern for different aspects of vehicle driving patterns. For example, the time series of driving distance and the driving/parking status of vehicles along the day are essential to enable the detailed EV integration researches such as EV day-ahead charging energy planning, EV coordinated scheduling investigation. Besides, many driving pattern studies currently are based on the GPS data which are collected from limited number of vehicles in confined area. As the power system analysis usually covers a larger scope, it will improve the accuracy of EV integration study if the driving patterns are studied with the data from a more comprehensive sample space. At present, a thorough study on the detailed driving patterns for EV integration studies in the Nordic region is missing. References [44, 45] studied the driving patterns of Denmark based on the Danish National Travel Survey. Following the work in [44, 45], this paper presents a method to convert the survey data of persons in the National Travel Surveys of the Nordic countries to the daily driving patterns of private passenger cars. The daily driving patterns of vehicles are investigated for EV integration study in the Nordic region. The driving distance and the EV charging/discharging availabilities are obtained according to the driving behaviors and status of vehicles along the day.

The rest of the paper is arranged as follows. The method of the driving pattern analysis is described in Section 2. The results of driving pattern analysis regarding the driving distance and EV charging/discharging availabilities in the Nordic area are presented in Section 3, followed by conclusions.

2 Methodology for driving pattern analysis based on national travel survey

In the driving pattern analysis for EV integration studies, it is important to obtain the EV driving behaviors. Currently, it is difficult to obtain statistically significant data of the daily driving behaviors of EVs directly. Due to the limitation of the current EV driving range and refueling support compared to the conventional internal combustion engine vehicles, the drivers with moderate driving requirements are more likely to use EVs at present and there are very few EVs for daily driving on the road. Therefore, the sample space is relatively limited and the driving pattern is not general. However, the study in Rautiainen of the year 2012 shows that PHEVs can be driven practically in the same way as the conventional internal combustion engine (ICE) vehicles. Further, with a large scale deployment of EVs and sufficient support of charging facilities, the driving pattern of EVs shall be more or less same as the conventional passenger cars since all the daily driving requirements should be fulfilled. Therefore, it is feasible to use the driving pattern of conventional passenger cars in the Nordic area to estimate the driving pattern of EVs. The National Travel Surveys of four countries are the most comprehensive data sources which have enough samples to represent the travel behaviors statistically in the corresponding Nordic country. Detailed information of the drivers as well as the driving behavior records in one particular day is contained in the national travel survey datasets.

2.1 From survey respondents to vehicles

The datasets from the National Travel Surveys provide the driving behaviors of survey respondents. The detail information of other driving license holders (if there are any) behavior in the household of respondents is not available. Such feature of the national survey datasets may lead to inaccurate outcomes if the datasets are used directly in EV driving pattern analysis since the driving behaviors can be different between the individual respondents and the individual vehicles. The driving requirement would be underrated, and the EV charging and discharging availability may be overestimated. For instance, in case of one car and two household members with a driving license in the household, the car could drive twice distance as the result of using the data directly.

In order to deal with the issue discussed above, a statistical process was used to transform the daily driving behavior observations of individual respondents to the behavior of individual vehicles. The steps of the process are illustrated in the flowchart shown in Fig. 1.

The datasets of the National Travel Surveys were divided into four categories according to the numbers of the driving license holders and the cars in the household of the respondents and processed differently. Four categories of the dataset are listed as follows:

Category 1: The car number equals to the number of the driving license holders in the household of the respondent.

Category 2: There are one car and two driving license holders in the household of the respondent.

Category 3: There are one car and three driving license holders in the household of the respondent.

Category 4: Others.

For Category 1, the driving behaviors of the respondents are considered as same as the driving behaviors of one car

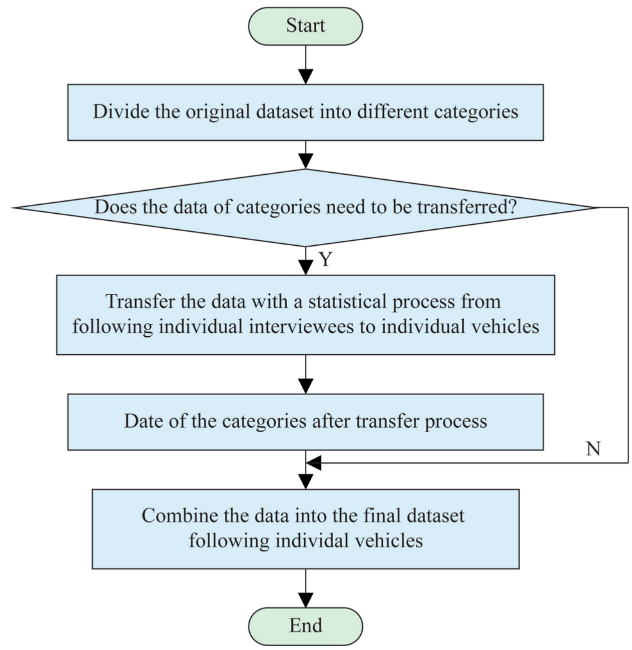

Fig. 1 Main steps of process to transfer dataset from following individual interviewees to individual vehicles

in the household. Such assumption is statistically reasonable if each driver only drives his/her own car or the driving behaviors distribute equally among all the cars in the household. Bias on the driving patterns is introduced with such assumption under certain situations. For example, the cars in the household may be functionally divided such as daily commuting and leisure driving for all the drivers in some cases when there is more than one car in the household. However, the size of the bias is small and is assumed to have a small effect on the results of the study.

For Category 2, the driving behaviors of the car cannot be assumed to be the same as the driving behaviors of the respondent. A transformation process is introduced in this case. With the assumption that similar drivers have similar driving patterns statistically, the other respondents in the dataset with the same characteristics as the other driver in the household of the main respondent is selected under a statistical process to imitate the main respondent's driving companion for sharing the car.

The driving behaviors of the imitative companion and the main respondent are combined to constitute the driving behaviors of the car. The imitative driving companions and the other driver in the household of the main respondent should have the same characteristics such as gender, age (difference within 5 years), the same recorded day of the week (weekday, Saturday or Sunday), etc. Their driving activities are checked with the driving activities of main respondent. There shall not be any overlap during the driving periods of two drivers throughout the day. A further but reasonable assumption is that the car can only be exchanged at home. The process is explained in more details in [45].

For Category 3, a similar transformation process is done as Category 2. However, there is an extra matching process for the imitation of second driving companion of main respondent.

Category 1 to Category 3 mentioned above make up the majority of the whole datasets of the National Travel Surveys. By combining Category 2 and Category 3 after transformation processes with Category 1, the datasets of detailed driving records following individual vehicles are created. The other observations outside all the three categories are less than 6% of the whole datasets and left out of the analysis.

2.2 Driving distance

The driving distance is one of the most important parameters of driving requirements which needs to be fulfilled in EV integration study. Consequently, it will affect the charging requirement and discharging operation possibility of EVs.

The data in the National Travel Surveys contain the starting time, ending time and driving distance of all the trips in a day. The cumulative driving distance can therefore be calculated accordingly. At the end of one trip, the driving distance of trip is cumulated. Following the records of all the trips in the day, the cumulated driving distance of vehicle along the day is obtained. Figure 2 shows an example of cumulative driving distance of a car along the day.

2.3 EV availability

In the integration study of EVs, the charging or discharging availability is also very important. The EV availability describes the available time slot when they are parked and can be charged or discharged during the day. With different EV charging and discharging possibility

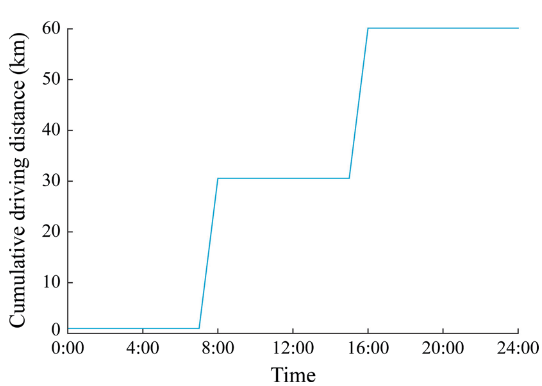

Fig. 2 Cumulative driving distance of a vehicle along the day

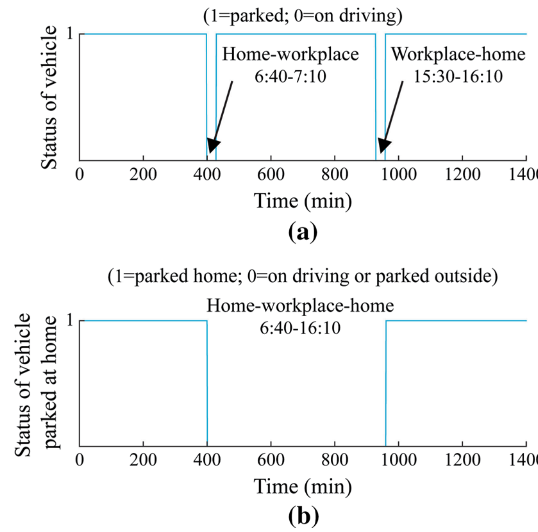

Fig. 3 Driving and parking status of a vehicle along the day

assumptions, two types of EV availabilities are studied in this paper, including EV availability all day and EV availability at home. The EV availability all day refers to the situation that EVs can be charged or discharged in a day whenever they are parked. EV availability at home refers to the situation that EVs can only be charged or discharged when they are parked at home.

Besides the driving distance, starting time and ending time, the driving records in the National Travel Surveys also provide the information of starting position and the destination of trips. According to the time and position information of all the trips in a day, the driving and parking status of vehicles can be determined in a minute. Figure 3 shows the examples of the vehicle status along the day with two different conditions. The status shown in Fig. 3a is the driving and parking status all day regardless of the parking place, which is associated with EV availability all day. The status shown in Fig. 3b refers to the driving and home parking status which is associated with EV availability at home.

Based on the status of vehicles in every minute, EV availabilities are calculated by hour and by quarter accordingly. They show the percentages of EVs available for charging or discharging during the specific period of a day. The availabilities of all the vehicles are averaged to obtain the mean EV availabilities along the day.

3 Results and discussions

3.1 Driving distance analysis

The daily driving distance is one of the key inputs for charging demand and the grid integration analysis of EVs.

Table 1 Average daily driving distance in Nordic region

Country	Driving distance (km)		
	All days	Weekdays	Weekends
Denmark	40.0	43.4	32.0
Finland	46.8	45.2	51.0
Norway	35.6	36.6	33.2
Sweden	32.0	35.2	30.6

In the Nordic area, the daily driving distance of vehicles is not very high. The average daily driving distances of Nordic region are listed in Table 1. The results of driving distance analysis are consistent with the average driving distance data from the statistical data of four mentioned Nordic countries.

All the four Nordic countries have an overall average driving distance less than 50 km per day, which is not a very long distance and can be supported by the current EV technologies. Specifically, Sweden has the shortest average driving distance among four countries while Finland has the highest number. In Denmark, Norway and Sweden, the average daily driving distance on weekdays is longer than that on weekends. However, it is in the opposite way in Finland. It shows a relatively long driving distance with 51 km in Finland on weekends. This is mainly due to more active driving behaviors and longer driving distance for trips to the second homes, the culture event, sports event, entertainment, restaurants and social evenings on weekends in Finland.

Figure 4 shows the cumulative driving distance on weekdays and weekends, respectively. The curves of the cumulative driving distance of four counties have similar trends on weekdays. The driving distances start to accumulate in the morning and have a rapid increase in the evening. Eventually, they reach the final plateau at around 24:00 at the end of the day. On the other hand, the cumulative driving distances in Denmark, Norway and Sweden form the curves with more gentle slopes on weekends. The distance in Finland increases steadily and rapidly from the morning to the evening and results in the relatively long driving distance on weekends.

In Nordic region, the daily driving distances of most of the vehicles are in the short distance range. Such everyday driving distance distribution provides a high possibility for EV integration. The daily driving distance distributions of Nordic region are as shown in Fig. 5 and Table 2.

About 64% of the vehicles in Denmark and 65% of the vehicles in Finland have a driving distance less than 40 km per day. The percentages in Norway and Sweden are about 73% and 74%, respectively.

Such a feature is more obvious on weekends. Figure 6 and Table 3 show the daily driving distance distributions of Nordic region on weekends. Over 75%, 77% and 78% of the vehicles in Denmark, Norway and Sweden have a daily driving distance less than 40 km on weekends, respectively. The percentage for Finland is about 66%, showing the more active driving behaviors in Finland on weekends.

It is shown that people drive more often on weekdays than on weekends in Denmark as the vehicles are mainly

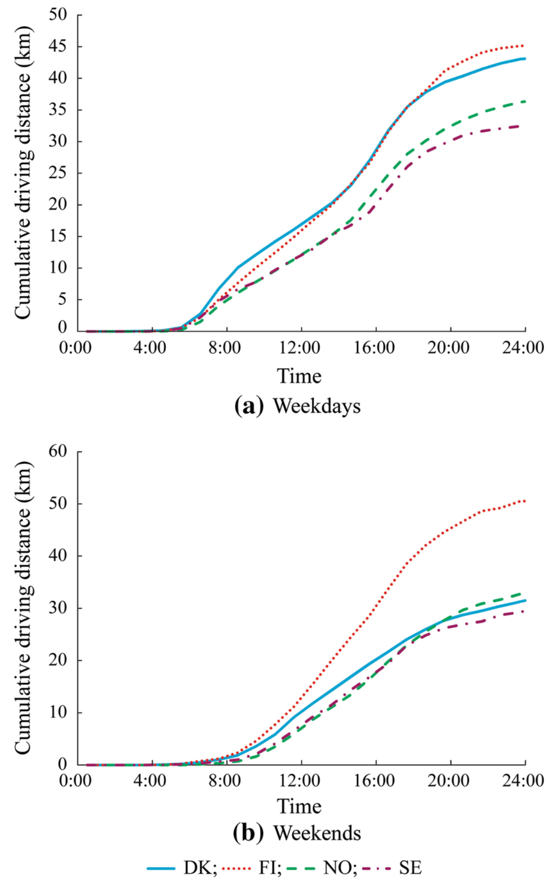

Fig. 4 Cumulative driving distance in Nordic region

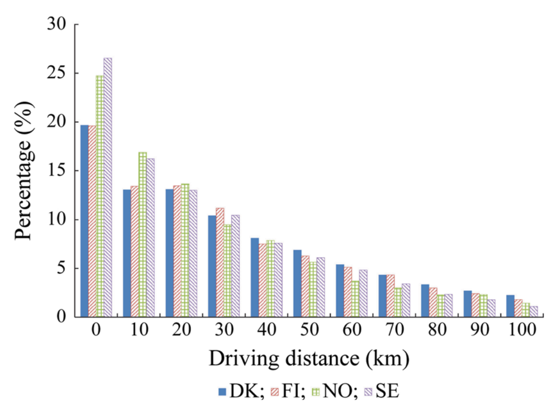

Fig. 5 Daily diving distance distribution in Nordic region on weekdays

Table 2 Cumulative daily driving distance distribution in Nordic on weekdays

Distance (km)	Driving distance distribution (%)			
	Denmark	Finland	Norway	Sweden
0	19.7	19.6	24.8	26.6
10	32.7	33.0	41.6	42.8
20	45.8	46.4	55.3	55.8
30	56.2	57.6	64.8	66.2
40	64.3	65.1	72.6	73.8
50	71.2	71.4	78.3	79.9
60	76.6	76.5	82.0	84.8
70	80.9	80.8	85.0	88.2
80	84.3	83.8	87.3	90.5
90	87.0	86.2	89.6	92.3
100	89.2	88.0	91.1	93.4
150	95.1	93.7	95.5	96.9
200	97.5	96.2	97.5	98.2
250	98.5	97.7	98.4	98.8
300	99.1	98.4	98.8	99.2
350	99.4	99.1	99.3	99.4
400	99.6	99.4	99.5	99.5
450	99.8	99.7	99.7	99.7
500	99.8	99.8	99.7	99.7
600	99.9	99.8	99.9	99.9
700	100.0	99.9	99.9	99.9
800	100.0	99.9	100.0	100.0

for daily commuting purpose between home and workplace. The driving activities are more active in Finland than the other three countries, especially on weekends. Norway and Sweden show moderate driving distances on both weekdays and weekends. The daily driving distance will not only have important impacts on EV battery sizing but also EV charging energy planning to the power system. The higher driving distance in Finland will possibly lead to higher pressure for energy planning of EV charging. However, the generally low daily driving distance is conducive to the EV promotion and EV integration to the power system in Nordic region.

3.2 EV availability analysis

The EV availability shows the possibility to be available for integration operations to the grid during the specific period of a day. EV availabilities vary with different charging/discharging supports of the power grid. In this paper, two types of EV availabilities are studied with two assumptions on the EV charging/discharging condition as mentioned in Section 2. The two types of EV availabilities include EV availability all day and EV availability at home.

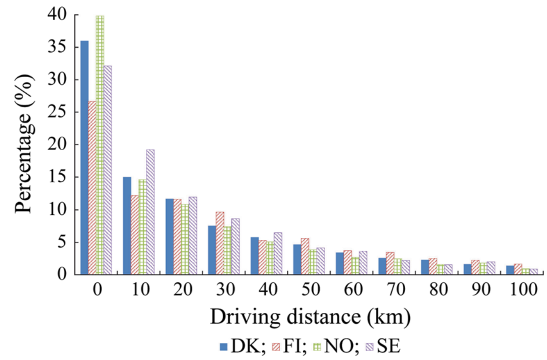

Fig. 6 Daily driving distance distribution in Nordic region on weekends

The EV availability all day is determined according to the parking status of vehicles. The vehicles are considered available for the grid integration operations when they are parked throughout the day. The EV availabilities all day by hour of four Nordic countries on weekdays and weekends are shown in Fig. 7. It is shown that the EV availability all day of all the four Nordic countries on both weekdays and weekends are at a high level. For most of the time in a day, the average availabilities in all the four countries are over 90% except that it is about 89% in Sweden at around 17:00 on weekdays. Table 4 shows the lowest EV availability all day in the four Nordic countries.

The EV availabilities all day in all the four Nordic countries have similar patterns. On weekdays, there are two obvious valleys in curves of EV availability all day, one in the morning at about 8:00 and the other one in the afternoon during 16:00 to 17:00. Such characteristic is consistent with the traffic hours when people go to work in the morning and come home from work in the afternoon. On weekends, the curves of EV availability all day are smoother. The EV availabilities start to drop gradually in the morning and climb up steadily in the evening. Different from the case on weekdays, the EV availabilities do not increase again in the morning and stay on a plateau in the middle of the day on weekends. Such difference is because that there are very few driving behaviors for work on weekends. Therefore, the W-shape curves which are closely related to the driving and parking behaviors for work commutes on weekdays does not show up on weekends.

For the regulating power market in Nordic region, the ramp-up or ramp-down time interval is 15 min. Consequently, the EV availability by quarter is needed for certain studies such as the research on the possibility of EVs to participate in the ancillary service of the power grid. Figure 8 shows the EV availabilities all day by quarter of the four Nordic countries on weekdays and weekends, respectively. There are some fluctuations during the driving activities active hours of the day. However, the curves of

Table 3 Cumulative daily driving distance distribution in Nordic on weekends

Distance (km)	Driving distance distribution (%)			
	Denmark	Finland	Norway	Sweden
0	36.0	26.7	39.8	32.1
10	50.9	38.9	54.4	51.3
20	62.6	46.4	55.3	55.8
30	70.2	50.5	65.3	63.3
40	75.9	60.2	72.7	72.0
50	80.6	65.5	77.8	78.4
60	84.0	71.1	81.6	82.6
70	86.6	74.9	84.3	86.2
80	88.9	78.3	86.8	88.4
90	90.5	80.8	88.3	89.9
100	91.9	83.1	90.1	91.9
150	95.7	84.7	91.1	92.8
200	97.7	91.2	94.0	96.2
250	98.6	94.2	96.1	97.6
300	99.2	96.0	97.5	98.3
350	99.5	97.3	98.7	98.9
400	99.7	98.0	99.4	99.4
450	99.8	98.9	99.8	99.6
500	99.9	99.3	99.8	99.8
600	100.0	99.6	99.9	100.0
700	100.0	99.9	99.9	100.0
800	100.0	100.0	100.0	100.0

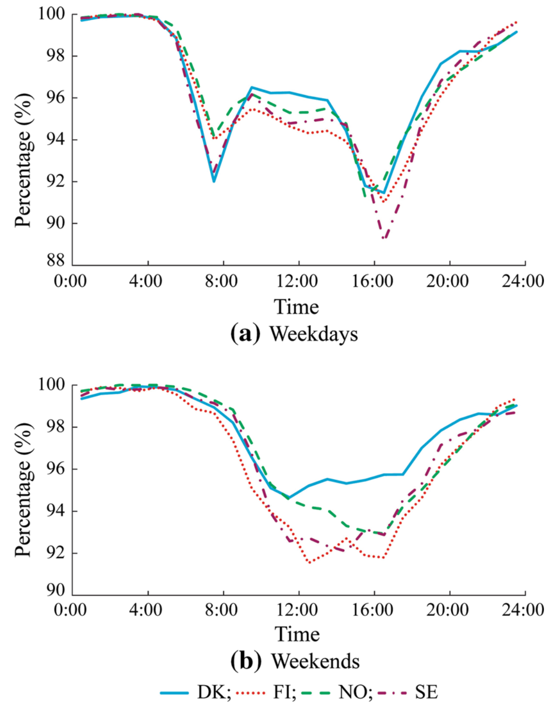

Fig. 7 EV availabilities all day by hour in Nordic regionand

Table 4 Lowest EV availability of Nordic region

Days	Lowest EV availability (%)			
	Denmark	Finland	Norway	Sweden
Weekdays	91.5	91.0	91.3	89.1
Weekends	94.7	91.5	92.9	92.1

EV availability all day by quarter have the same trends with the curves by hour.

In certain studies of EVs, such as the research on EV home charging, only the home parking status is of interest and the EV availability at home shall be used in such studies. For the EV availability at home, the vehicles are considered available for the grid integration operations only when they are parked at home. The EV availabilities at home of the four Nordic countries on weekdays and weekends are shown in Fig. 9. The EV availabilities at home have much lower values than the EV availabilities all day in all the four Nordic countries in the daytime.

Table 5 shows the lowest EV availability at home during the day in the four Nordic countries. The lowest availabilities drop to the ranges around 50% on weekdays and 70% on weekends. The EV availabilities at home have similar patterns and values in the Nordic region. On weekdays, the EV availabilities at home in the Nordic region start to decrease in the morning at about 7:00, stay at a relatively low level and increase again in the afternoon when people start to return home. On weekends, the curves of EV availability at home are smoother which is similar to the situation of the EV availability all day.

Figure 10 shows the EV availabilities at home by quarter of the four Nordic countries on weekdays and weekends, respectively. Similar to the situation of the EV availability all day, there are some fluctuations in the curves by quarter during the driving activities active hours of the day, and the curves by quarter and the curves by hour have the same patterns.

The EV availabilities are important to the EV integration study as they indicate the possibilities of the EV charging or scheduling. The results suggest that most of the vehicles can be scheduled during the night time. Such characteristic supports the ideas of shifting the EV charging load to the low-demand period and EV coordinated scheduling with wind power at night. However, the results also suggest that most of the charging or the scheduling should be finished before 7:00 in the morning on weekdays. Furthermore, if the public charging facility is available, a high potential for EV scheduling will be available between 10:00 and 15:00 on weekdays in Nordic region, which suggests a possibility of the EV scheduling with the solar power in the day time.

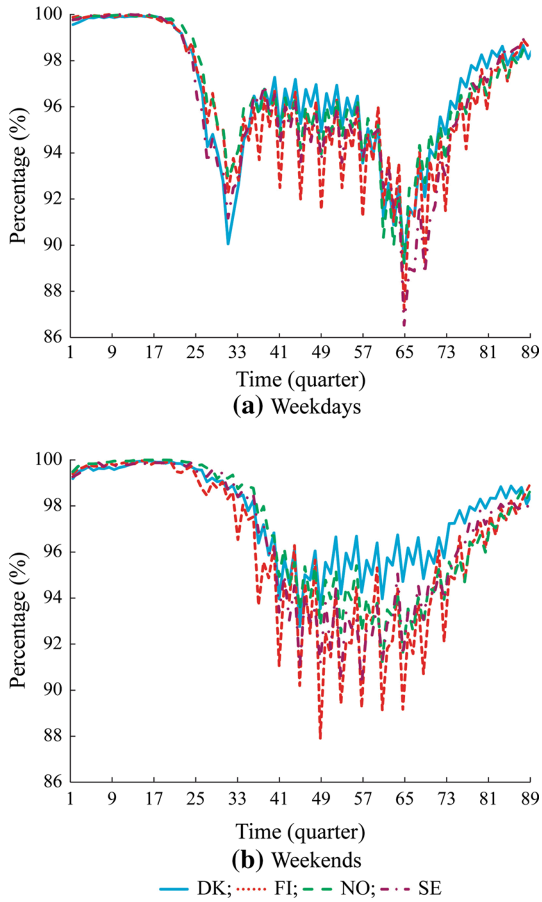

Fig. 8 EV availabilities all day by quarter in Nordic region

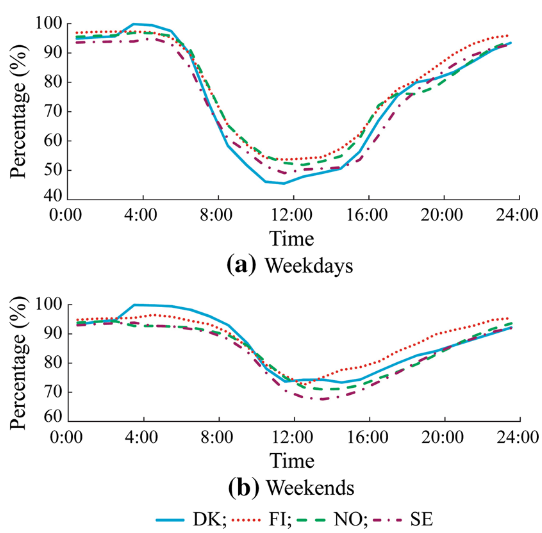

Fig. 9 EV svailabilities at home by hour in the Nordic region

Table 5 Lowest EV availability at home of Nordic region

Days	Lowest EV availability (%)			
	Denmark	Finland	Norway	Sweden
Weekdays	45.5	53.7	51.9	49.1
Weekends	73.4	72.6	71.0	67.6

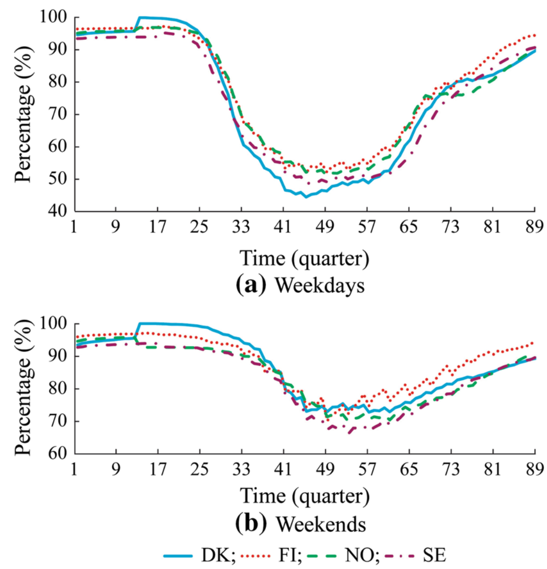

Fig. 10 EV availabilities at home by quarter in Nordic region

4 Conclusions and future work

This paper presents a methodology for the driving patterns of private passenger cars in the Nordic region based on the data from the National Travel Surveys. The results of the analysis show that the daily driving distance of vehicles in the Nordic region can be met by EVs. Most of the vehicles in the Nordic region have a short driving distance per day. The EV availability all day is quite high as most of the daily trips have a short driving distance. The availabilities are about or above 90% for most of the time in the day. Two obvious drops corresponding to the morning and afternoon peak hours can be seen in the curves of all the four studied Nordic countries on weekdays. When the charging condition is restricted to home parking, the EV availability at home is lower during the day. The lowest availabilities are in the ranges around 50% on weekdays and 70% on weekends. The driving patterns of the vehicles are different on weekdays and weekends in the Nordic region. The variance of the driving patterns of the vehicles under different conditions may have important impacts and need to be considered in the detailed EV integration studies.

The driving pattern analysis in this paper studies the daily driving distance and the EV availabilities for the EV integration research in the Nordic region. However, the stochastic characteristics of the driving patterns of the vehicles are not investigated in this paper. The stochastic features of the daily driving patterns may have considerable impacts on some of the EV integration studies such as smart charging and the V2G optimal operation analysis. This will be investigated in the future work.

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